2020 DOE Vehicle Technologies Office Annual Merit Review

Integrated Motor and Drive for Traction Applications

Project ID: elt243

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University of Wisconsin-Madison

June 1-4, 2020

WEMPEC

Overview

Timeline

- Project start date: 4/01/2019
- Project end date: 3/31/2024
- Percent Complete: 20%

Budget

- Total project funding
  - DOE's share: $ 1,500,000
- Funding for FY 2019: $ 300,000
- Funding for FY 2020: $ 300,000

Barriers and Technical Targets

- Multi-physics integration of power electronics with machine to enhance performance metrics
- High-temperature power electronics availability and cost
- High-performance machine materials availability and cost
- Advanced thermal management for machine & power electronics

Partners

- Oak Ridge National Laboratory (ORNL)
- National Renewable Energy Laboratory (NREL)

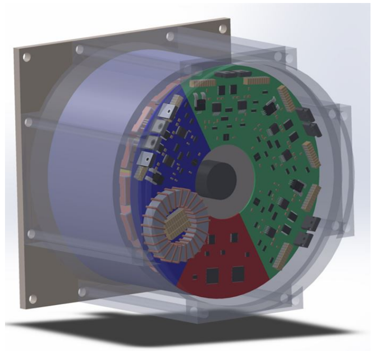
Relevance

Objective

- Pursue an aggressive research program to merge **high-torque-density traction machines** and **high-efficiency inverters** into state-of-the-art **integrated motor drives (IMDs)** packaged inside combined housings that will exceed existing traction drive performance metrics in several categories, as follows:

Electric Motor Requirements	
Metric	**Value**
Cost ($/kW)	≤ 3.3
Power Density (kW/L)	≥ 50
System Peak Power Rating (kW)	100

Power Electronics Requirements	
Metric	**Value**
Cost ($/kW)	≤ 2.7
Power Density (kW/L)	≥ 100
System Peak Power Rating (kW)	100



Impact of research

- Reduced overall mass and volume → Future EVs with higher power rating and efficiency
- Modular architecture → Reduced manufacturing cost and higher fault tolerance/reliability
- Co-packaged motor and drive → Higher power density with lower EMI emissions and reduced cost
- Shared thermal management system → Simplification leading to reduced coast and enhanced reliability

Our project aims to develop advanced IMD technology that will benefit Electric Vehicle manufacturers for achieving major performance improvements at lower cost

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Milestones for Budget Period 1

April 2019 to March 2020

Milestone Title and Description	Completion Date	Description of Verification Method	Status
Define machine and inverter configurations for trade-off study	09/30/2019	Review literature to identify initial list of machine and inverter topologies that deserver further investigation	Completed
Machine and inverter topology review	11/30/2019	Analyze machine and inverter candidates to evaluate trade-offs.	Completed
Down-select machine configurations	01/12/2020	Assign numerical rankings to machine and inverter topologies and down-select.	Completed
Inverter performance analysis with simulation	03/31/2020	Use simulation tools to predict inverter performance	Completed
Go/No Go Decision Title: Trade-off study for electric machine & inverter completed	01/12/2020	Use numerical rankings aligned with Table A performance targets to choose most promising candidates for further investigation	Completed

All planned tasks for Budget Period 1 successfully completed

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Milestones for Budget Periods 2 and 3

Milestones for Budget Period 2 (April 2020 to March 2021)

Milestone	Type	Description
Motor electromagnetic design	Technical	Perform the design of the electric machine and specify the machine parameters
PCB fabrication for benchtop prototype	Technical	PCB for benchtop prototype is designed and fabricated for testing
Motor mechanical design	Technical	Verify the mechanical design of the motor with ORNL and NREL, deliver the final design for prototyping
Performance analysis of benchtop prototype inverter	Technical	Evaluate the performance of the benchtop prototype inverter
Go/No Go Decision: Preliminary IMD Design Completed	Go/No Go	Drawings, schematics are ready for making the prototype motor and benchtop inverter.

Milestones for Budget Period 3 (April 2021 to March 2022)

Milestone	Type	Description
Detailed prototype machine and inverter design	Technical	Complete the detailed design of the prototype machine and inverter in preparation for fabrication
Fabricate prototype machine	Technical	Support fabrication of prototype machine
Fabricate prototype inverter	Technical	Complete the fabrication of the prototype inverter
Initial testing of prototype inverter and machine	Technical	Conduct inverter to verify their performance capabilities initial tests of prototype machine
Go/No Go Decision: Complete the fabrication of the prototype machine & inverter	Go/No Go	Complete fabrication of prototype machine and inverter including performance verification testing as components.

Approach

- **Perform trade-off study for IMD electric motor**
  - Investigate new ***motor topologies and material technologies***
  - Analyze ***state-of-the-art preliminary motor designs*** by performing analysis and FEA
  - Compare promising preliminary designs
  - Down-select most promising electric motor for IMD configuration from ***trade-off study***
- **Investigate promising IMD inverter topologies and conduct trade-off study**
  - Investigate most appealing inverter topologies for ***IMD*** traction applications
  - Investigate ***state-of-the-art technologies*** in power switches, passive components, and cooling
  - Perform trade-off study comparing ***Voltage Source Inverter (VSI) and Current Source Inverter (CSI) topologies***
  - Select most promising inverter topology and associated components for further development
  - Verify the performance of the selected motor drive configuration using analysis and simulation
- **Carry out preliminary IMD testbed preparation**

Technical Accomplishments and Progress

Achievements during Budget Period 1 (4/1/2019 to 3/31/2020)

Motor

- Investigated alternative motor types for traction application
- Developed preliminary designs of several Surface Permanent Magnet (SPM) machines
- Designed preliminary designs of spoke-type and V-shape Internal PM (IPM) machines
- Performed tradeoff study to select the best IMD traction motor candidates (Pugh analysis)

Inverter

- Investigated alternative inverter topologies, including VSI vs. CSI comparisons
- Analyzed applicability of available Wide Bandgap (WBG) devices and passive components
- Performed trade-off study to select the best IMD inverter candidates (Pugh analysis)

IMD (Combined Motor and Inverter)

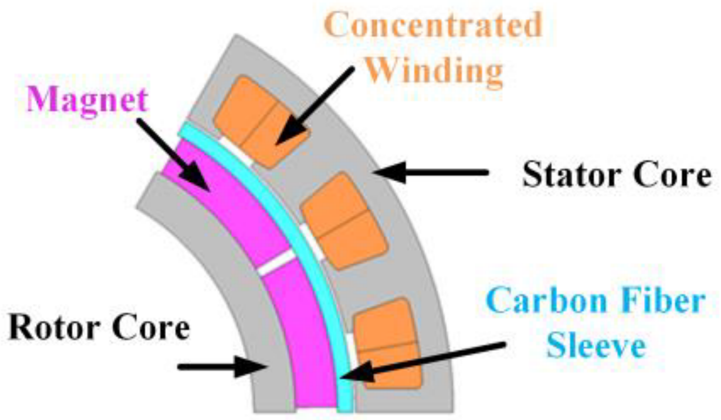
- Performed trade-off study to select the preferred IMD motor/inverter configuration (Pugh analysis)
- Prepared preliminary IMD testbed for next phase of project

Focus throughout work to date has been on optimizing the combined IMD system

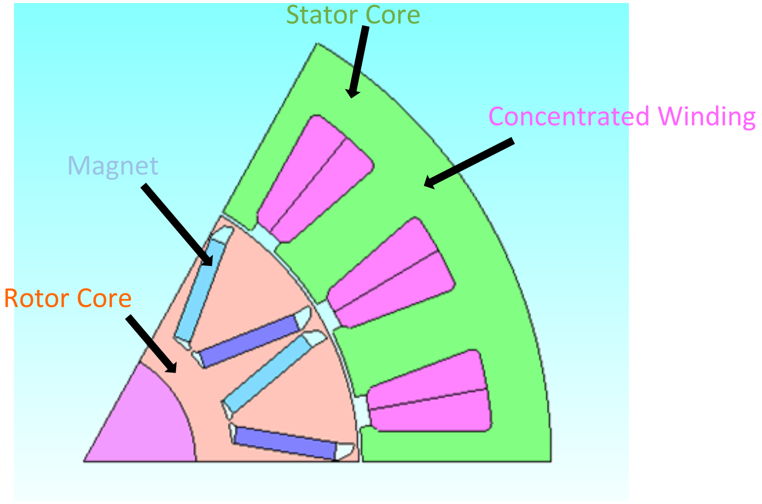
Technical Accomplishments and Progress

Motor Tradeoff Study

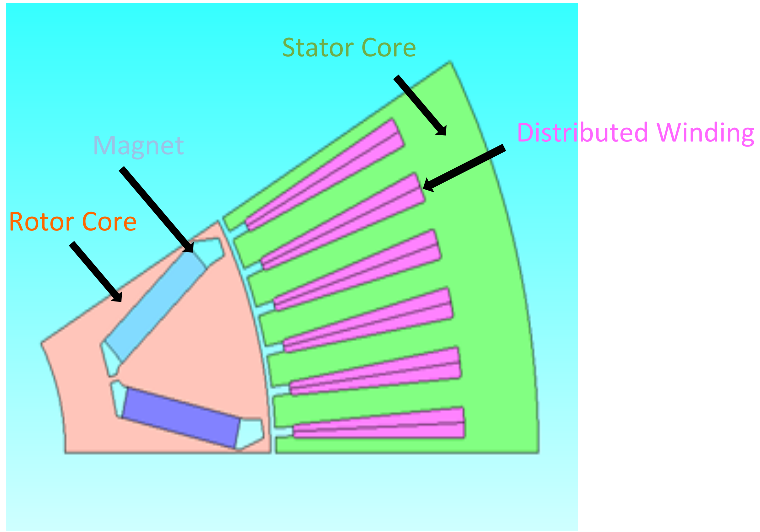
SPM Machine with Concentrated Windings



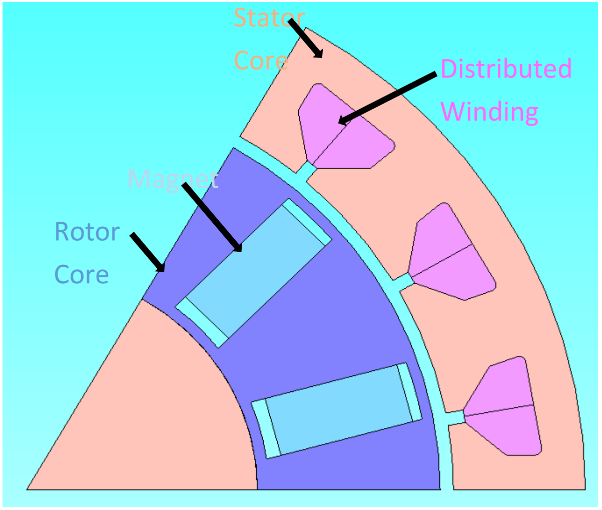
V-shape IPM Machine with Concentrated Windings



V-Shape IPM Machine with Distributed Windings



Spoke-Type IPM Machine with Distributed Windings



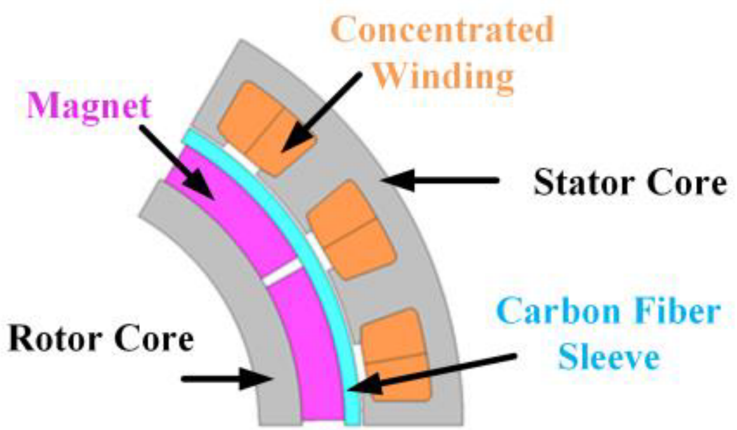
- Focus has been on PM machines because of their superior power density
- DOE guidelines have been followed to avoid magnets with heavy rare-earth materials and expensive lamination materials (e.g., CoFe)
- Attention focused on maximizing power density and minimizing cost

Several different types of permanent magnet machines have been investigated and compared for tradeoff study

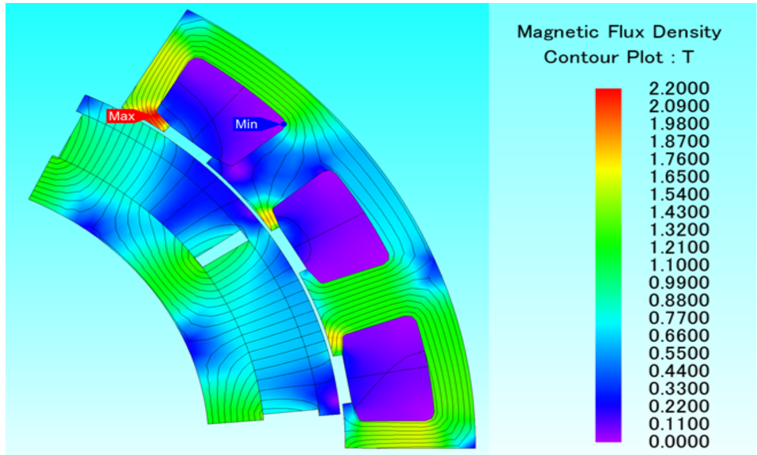
Technical Accomplishments and Progress

Example: Surface PM Traction Motor Design Details

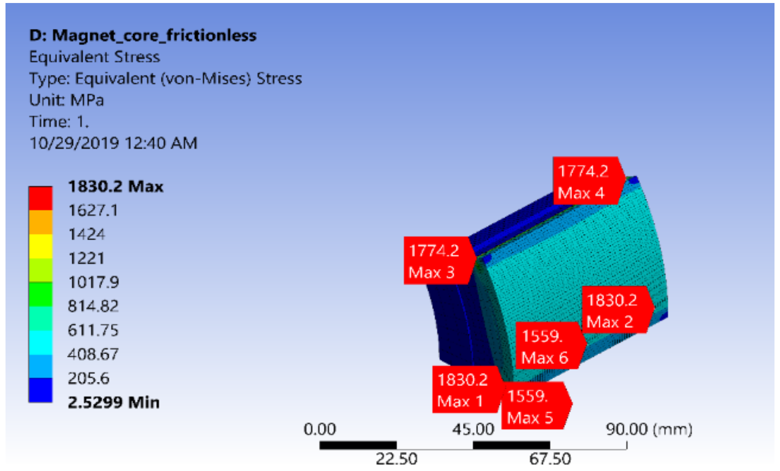
SPM Machine with Concentrated Windings



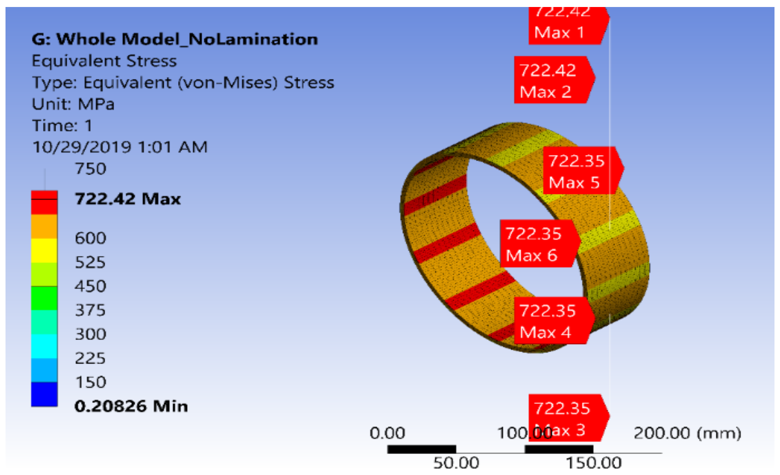
Flux Density Distribution in SPM Machine at Peak Torque



FEA-Calculated Von-Mises Stress:
Permanent magnets are bonded to sleeve and frictionless with rotor core



FEA-Calculated Von-Mises Stress:
Permanent magnets are frictionless with both sleeve and rotor core



Parameter	***Value***
Stator/rotor core material	10JNHF600 *Si Steel*
Magnet material	N38 NdFeB *No Dysprosium*
Stator slots / Rotor poles	18/12
Rotor corner speed [rpm]	3,200
Rotor max speed [rpm]	20,000
Rated/Peak Power [kW]	55/100
Power density [kW/l]	25.4
Efficiency @ 55 kW [%]	96.5

SPM machine is one of the promising machine candidates for IMD

Studies have been carried out for IPM machines as well.

Technical Accomplishments and Progress

Traction Motor Trade-off Results from Pugh Analysis

Criteria	Weight factor	SPM Machine		Spoke IPM		V-shape IPM	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Volume	5	5	25	4	20	4	20
Cost	5	3	15	3	15	4	20
Field weakening capability	5	5	25	5	25	5	25
Efficiency	5	5	25	4	20	4	20
High temperature capability	3	3	9	4	12	4	12
Mass	3	5	15	3	9	4	12
SC fault vulnerability	2	3	6	4	8	4	8
Modularity (Concentrated windings)	2	5	10	5	10	5	10
Noise	4	5	20	5	20	5	20
Score			150		139		147

Requirement specified in the SOPO

Requirement specified in the U.S. DRIVE roadmap

Other important requirements for electric machine

- The SPM machine has ***smaller rotor volume*** compared with other PM motor candidates with magnets inside rotor
- ***Less magnet*** is needed to produce the same torque for V-shape IPM motor → lower cost
- ***Optimal field weakening*** can be achieved by adopting fractional-slot concentrated windings
- The ***rotor losses*** in the SPM machine are lower than for other IPM machines → Higher efficiency with improved cooling
- The ***volume and mass*** of the SPM machine is smaller than for other IPM machines

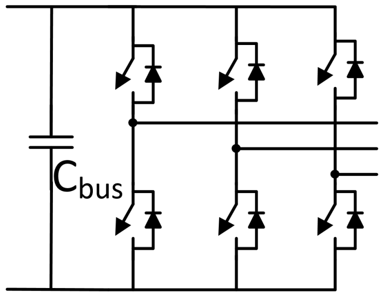
SPM machine rated the most promising candidate for IMD system, with V-shape IPM machine also ranking high in study

Technical Accomplishments and Progress

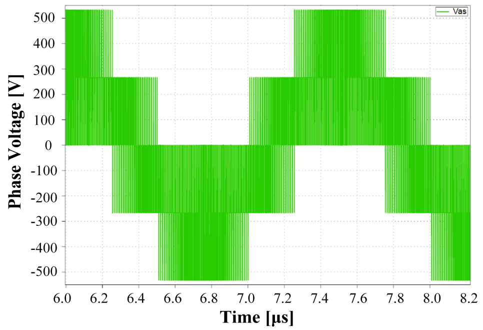
VSI vs. CSI Overview Comparison

	Topology	DC Link	Output Voltage	Common-Mode EMI

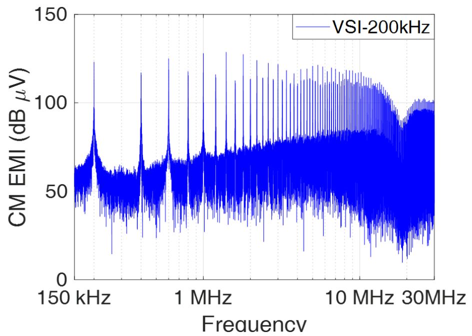
VSI



Fragile and temperature-limited

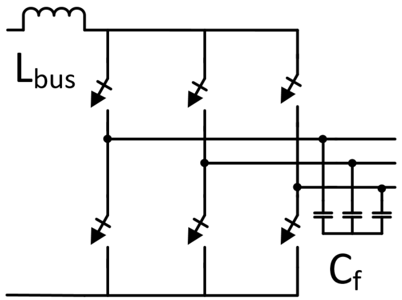


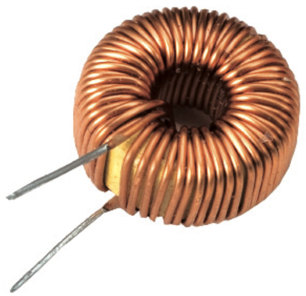
High dv/dt, creating motor insulation stress



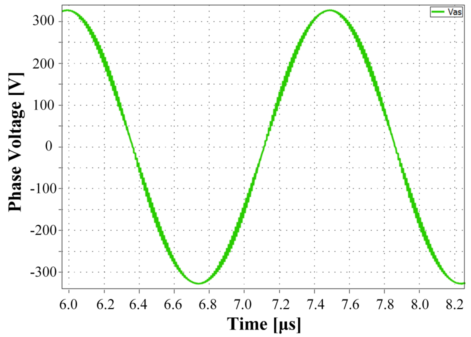
High Common Mode (CM) EMI and bearing current risk

CSI

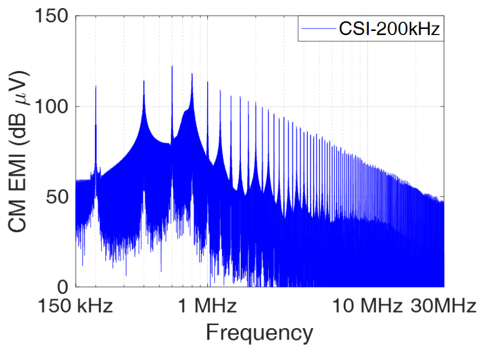




Rugged and capable of high temperature



Low-THD sinusoidal voltage and current waveforms



Integral LC filter provides appealing EMI roll-off

WBG-based Current-Source Inverter (CSI) overcomes many of the VSI limitations by significantly lowering output dv/dt stress, CM EMI emissions, bearing current risks, and temperature limitations

Technical Accomplishments and Progress

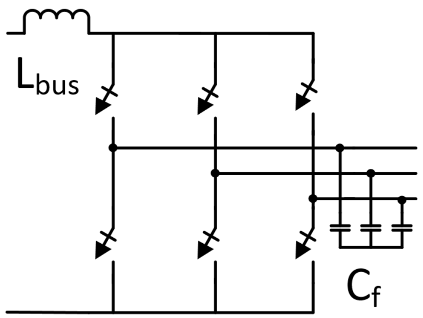
Output Power Capability of VSI vs. CSI for CPSR

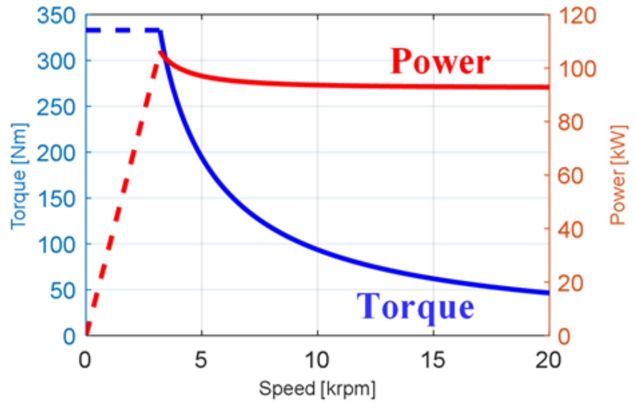
Topology

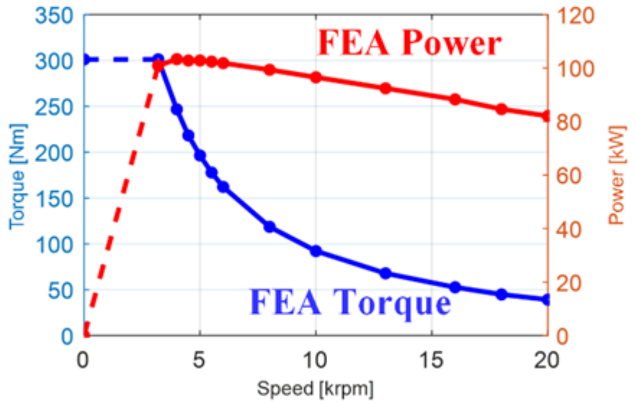
Analytically calculated torque-speed curve and power-speed curve

FEA calculated torque-speed curve and power-speed curve

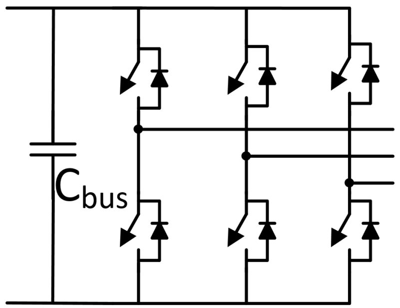
CSI

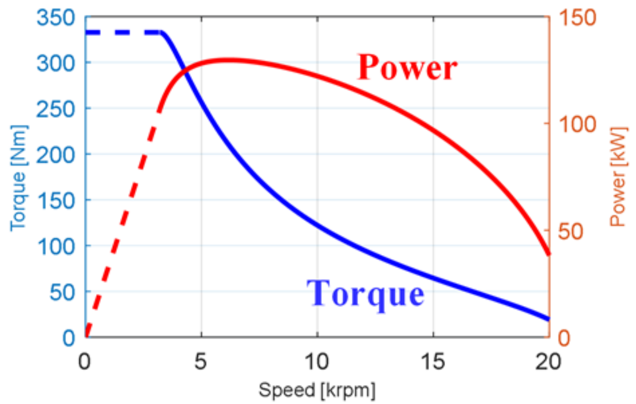


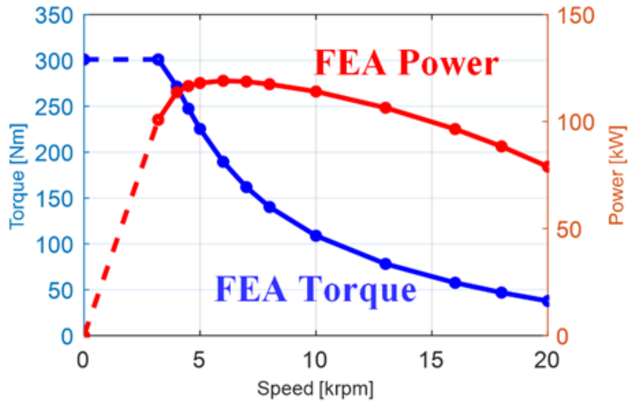




VSI



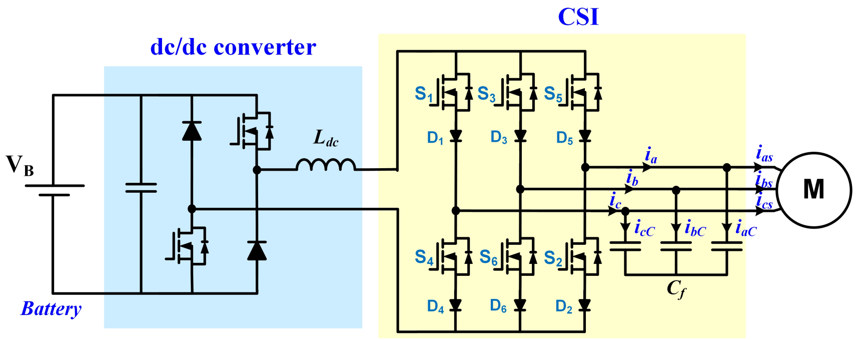




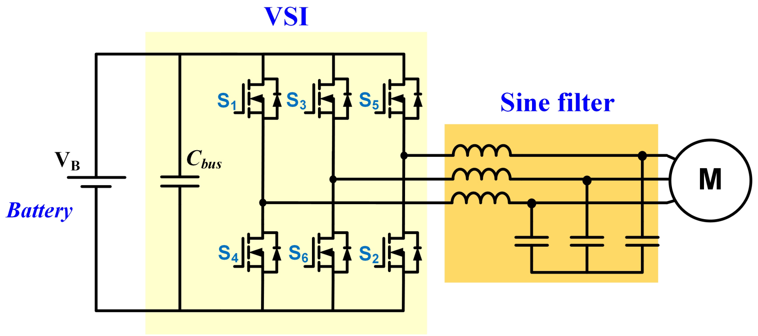
CSI operates as a boost-type inverter which offers advantages over VSI for traction motor applications by extending the constant-power speed range

Technical Accomplishments and Progress

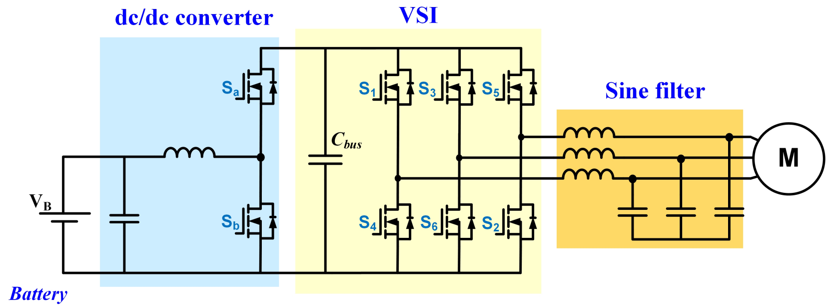
Efficiency Comparison of VSI and CSI Power Converters



2-Level CSI with DC/DC Converter



2-Level VSI with Sine Filter



2-Level VSI with Sine Filter and DC/DC Converter

RPM	Power (kW)	2-level CSI with dc/dc converter	2-level VSI with sine filter	2-level VSI with sine filter and dc/dc converter
3,200	55	98.79	98.89	98.63
3,200	100	98.07	98.38	97.99
20,000	100	98.12	98.51	98.05
Operating condition: 55 kW output power, 50 kHz switching frequency, 650 Vdc				

- Several power converter configurations were analyzed to compare their capabilities for meeting the DOE project performance metrics
- Modeled the VSI and CSI topologies in PLECS using device manufacturer's SiC device models to predict the efficiency
- Compared performance of power converters for predicted efficiency, EMI/EMC performance, and boost function of inverter output voltage for Constant Power Speed Ratio (CPSR) capability

2-level CSI with DC/DC converter and 2-level VSI with sine filter and dc/dc converter provide nearly the same field weakening and output voltage waveform quality, providing a fair comparison

2-level VSI with sine filter and dc/dc converter has lower predicted efficiency than the other two

Technical Accomplishments and Progress

Pugh Analysis of Inverter Candidates

Criteria	Weight factor	2-level CSI with dc/dc converter		2-level VSI with sine filter		2-level VSI with sine filter and dc/dc converter	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Volume	5	5	25	5	25	4	20
Cost	5	4	20	5	25	4	20
Field weakening capability	5	5	25	3	15	5	25
WBG capability	5	4	20	4	20	4	20
Efficiency	5	5	25	5	25	4	20
High temperature capability	3	5	15	4	12	4	12
Score			130		122		117

Requirements specified in the SOPO

Requirements specified in the U.S. DRIVE roadmap

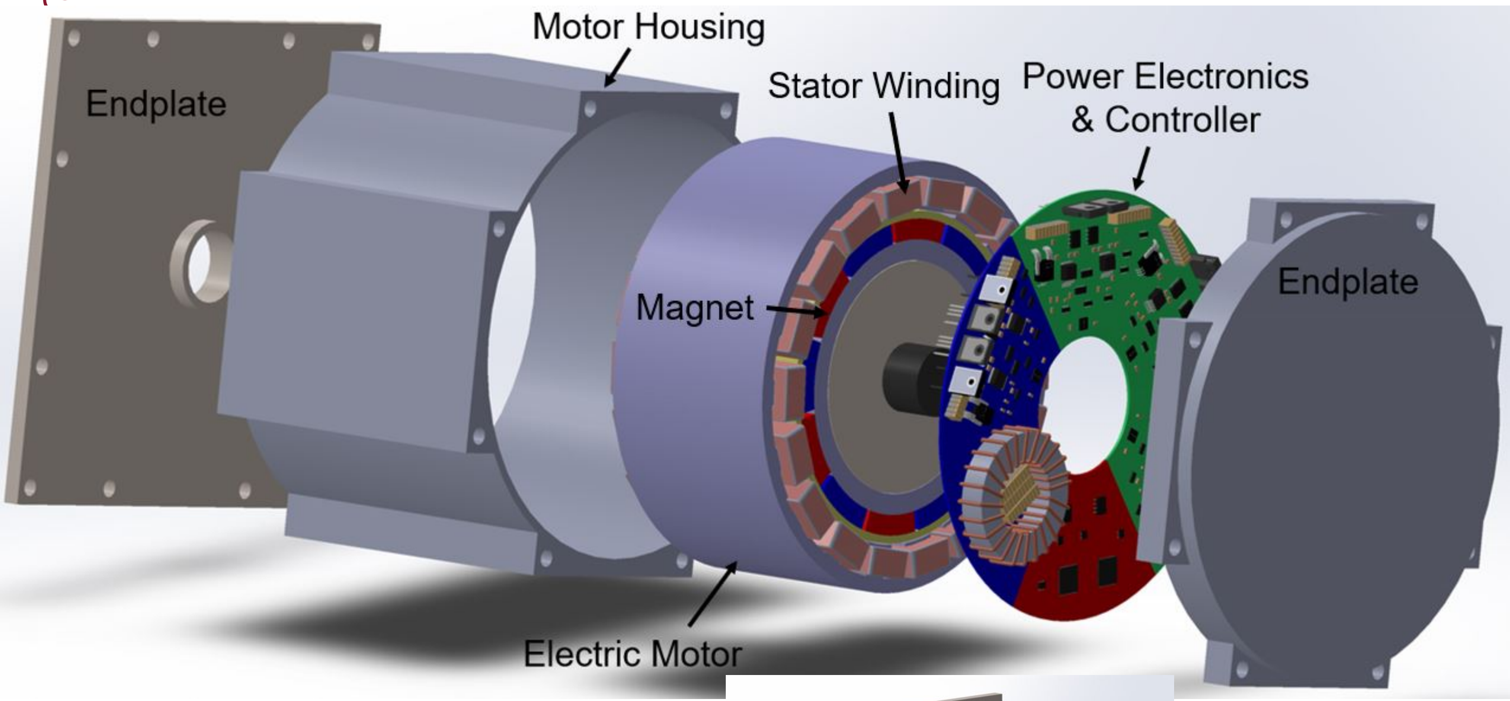
- Volume of VSI's sine filter penalizes its power density performance metric
- 2-level VSI with sine filter has ***fewest components*** → lowest cost
- The ***boost function*** of CSI and 2-level VSI with dc/dc converter both yield high CPSR capability
- Based on simulation estimates, 2-level CSI with dc/dc converter and 2-level VSI with sine filter have the ***highest efficiency*** predictions
- Replacement of the VSI's dc-link capacitor with an ***inductor*** in the CSI eliminates one of the most thermally-limiting power circuit components

2-level CSI with a dc/dc converter evaluated to be the strongest candidate topology for the IMD system based on trade study comparison

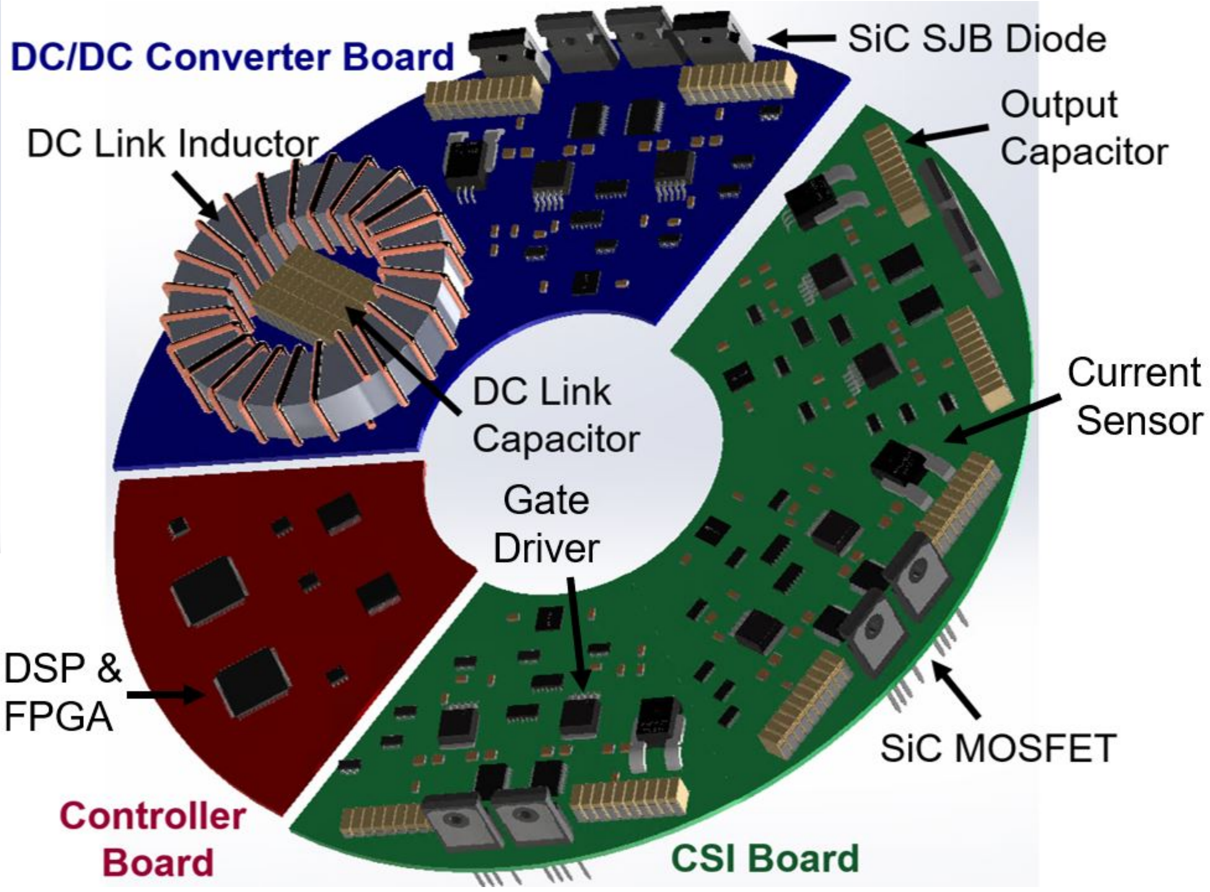
Technical Accomplishments and Progress

Preliminary IMD Configuration

IMD Exploded View

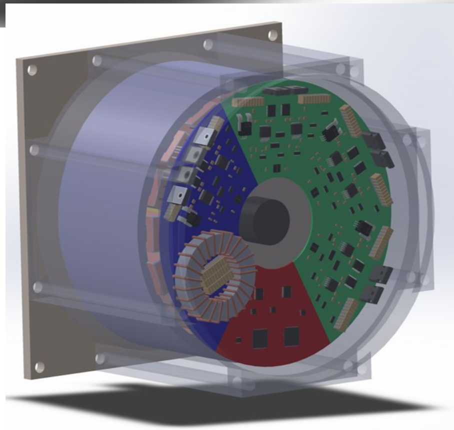


Preliminary Power Converter Layout



Notes:

- *Cooling not shown*
- *Housing and structure for illustration purposes only*
- *Detailed IMD design will be performed during next Budget Period*



Integrated IMD View

Axial-mounted power converter represents one promising topology for IMD configuration

Technical Accomplishments and Progress

Pugh Analysis of Integrated Motor Drive (Motor + Inverter)

Criteria	Weight factor	2-level CSI with dc/dc converter + PM machine		2-level VSI with sine filter + PM machine		2-level VSI with sine filter and dc/dc converter + PM machine	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
High temperature capability	3	5	15	4	12	4	12
EMI	4	3	12	3	12	3	12
Parts count	4	4	16	5	20	4	16
Weight	3	5	15	4	12	3	9
Fault tolerance	2	4	8	2	4	2	4
Modularity	2	1	2	1	2	1	2
Score			68		62		56

Requirements specified in the U.S. DRIVE roadmap

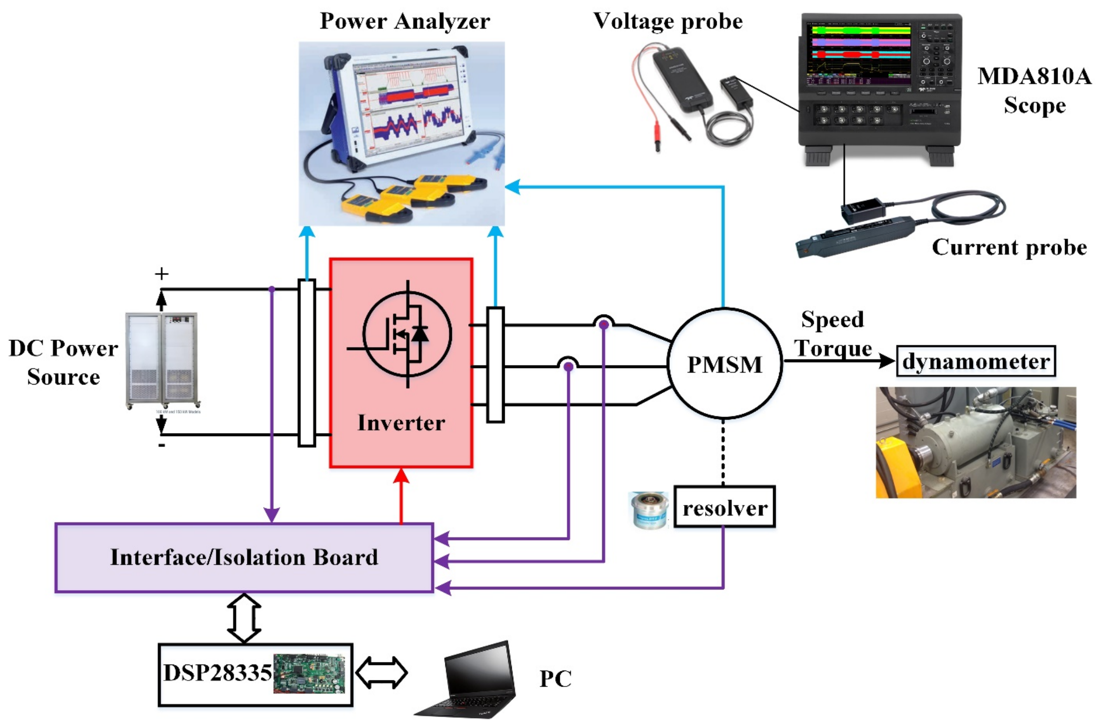
Other important requirements for IMD

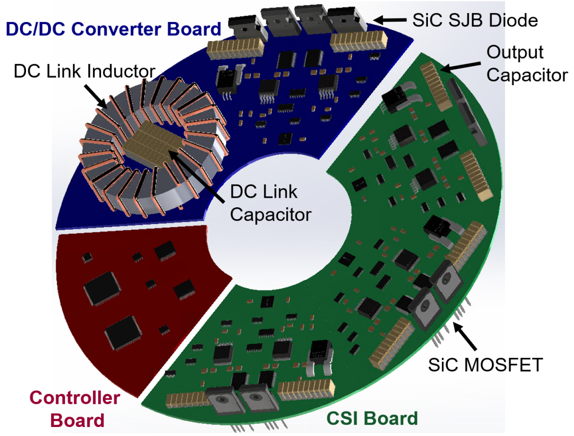
- Since our project focuses on ***IMD*** concept, an additional trade study was carried out to provide a composite score for IMD including both motor and inverter trade-off
- CSI holds advantages over VSI in IMD applications because of its better suitability for ***high-temperature operation*** in proximity to machine end windings
- IMD using 2-level VSI with sine filter has ***fewest components*** but it suffers in other metric categories
- IMD using the 2-level CSI with a dc/dc converter has the ***lowest number of passive components*** which helps to minimize power converter volume
- CSI is much better at surviving ***short-circuit*** faults with PM machines than VSI due to absence of free-wheeling diodes in CSI

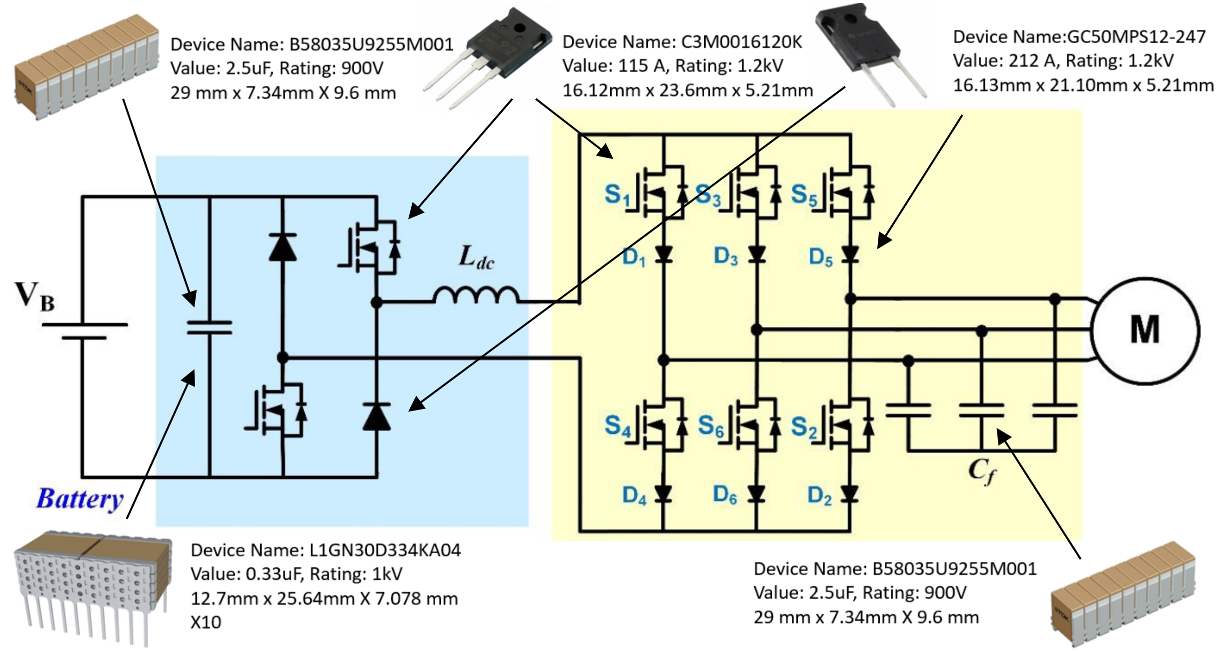
IMD configuration using 2-level CSI with dc/dc converter with PM machine has been selected as the preferred candidate for development during next phase of this project

Technical Accomplishments and Progress

Preliminary IMD Testbed Preparation







Our IMD testbed will include:

- High performance oscilloscope and probes
- Power analyzer
- DC power supply
- 4-Quadrant dynamometer

Components and equipment for high-performance IMD testbed are being procured

Responses to Previous Year Reviewer's Comments

- This is the first year that the project has been reviewed.

Collaboration and Coordination with Other Institutions

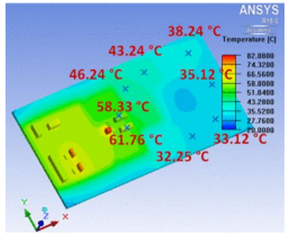
- **Oak Ridge National Laboratory (ORNL)**
  - UW-Madison participates in biweekly telecon meetings with ORNL and other participating universities to discuss the project progress and design requirements
  - Prof. Sarlioglu and Jahns and their students informally met with Dr. Ozpineci, Dr. Guijia Su, and Dr. Jason Pries of ORNL at the IEEE ECCE conference in Baltimore last September

- **National Renewable Energy Laboratory (NREL)**
  - Prof. Jahns visited NREL this year and initialized discussion about project with Dr. Sreekant Narumanchi who leads the thermal design group.
  - UW-Madison and NREL had follow-up telecons to discuss the project and collaboration opportunities

Partnership collaboration with National Labs will expand during 2nd project year

Remaining Challenges and Barriers

- Multi-physics integration of IMD to achieve optimal use of volume and cost
- Advanced thermal management for IMD to limit maximum temperatures of magnets and power converter
- Availability of high-temperature power electronics and high-performance machine materials at low cost

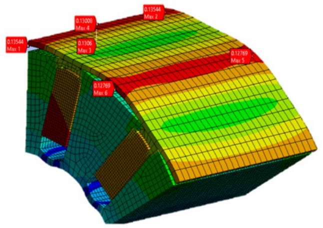


Thermal

Electric Machine

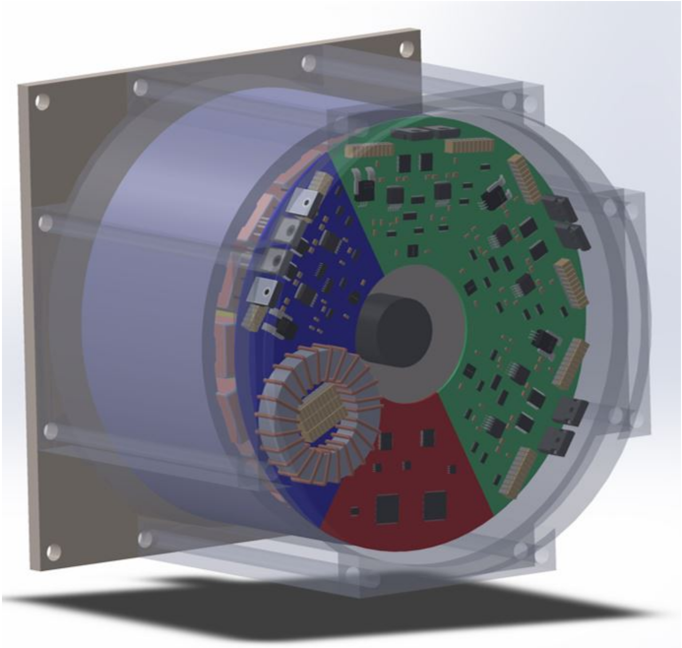
Power Electronics

Multi-Physics Design



Structural

Integrated Motor Drive (IMD)



IMD concept requires aggressive multi-physics design to optimize motor drive system for volumetric power density and cost

Proposed Future Research

Budget Period 2: Preliminary IMD Design

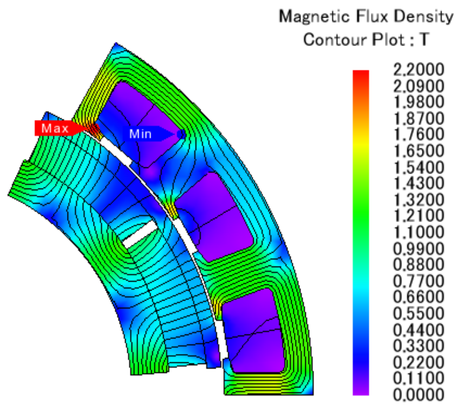
We plan to carry out following tasks:

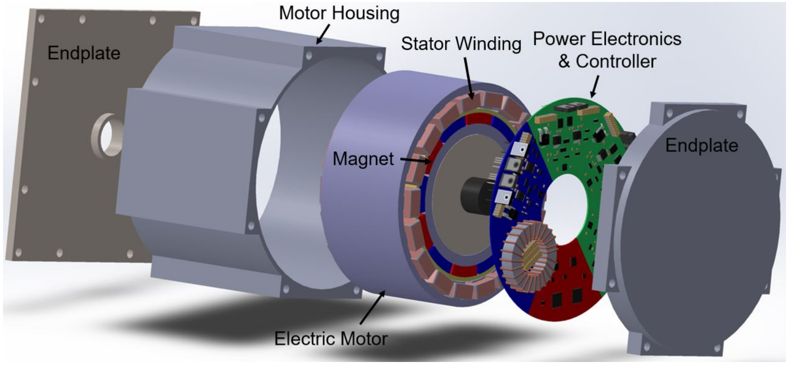
Task 2.1 – Electric Machine Design

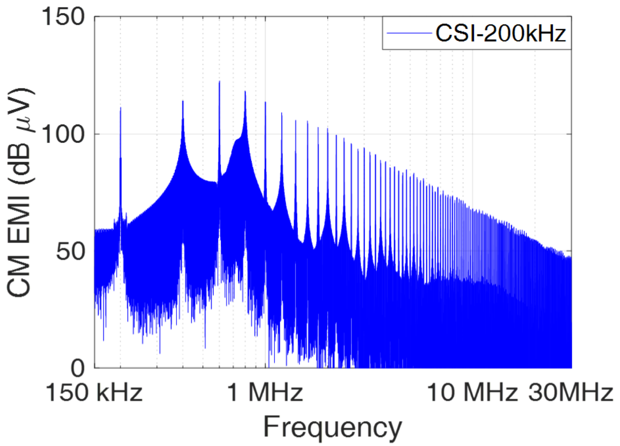
- Design electric machine using analysis, simulations, and FEA software to evaluate and optimize performance metrics
- Collaborate with ORNL and NREL to address multi-physics technical issues including mechanical, structural, and thermal design

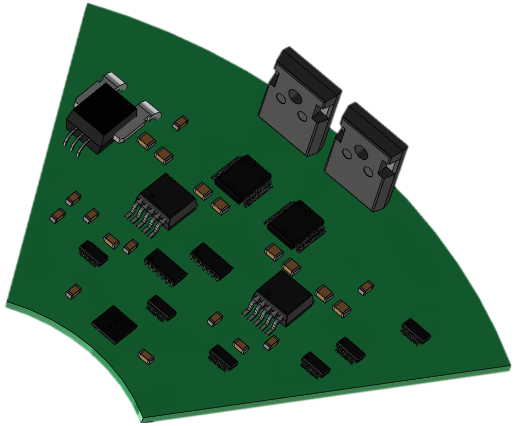
Task 2.2 – Development of Benchtop Prototype Inverter

- Evaluate all key performance metrics including power density, cost efficiency, and EMI/EMC characteristics
- Design gate drives, passive components, and controller unit
- Fabricate and test the benchtop inverter to retire technical risks









2nd year will provide critical opportunity to convert promising IMD concept into machine and inverter designs for rigorous multi-physics evaluation

Summary

- Integration of power electronics inside machine represents one of the most promising approaches for making major progress to reach challenging DOE performance metrics
  - Demands systems-oriented, multi-physics-based approach to achieve success
  - Opens promising avenues to boost power density and lower cost, with valuable additional benefits in areas such as reliability/fault tolerance
- First year of project has succeeded in identifying the most promising machine and power converter technologies for future IMDs to meet DOE metrics
  - Thorough trade-off studies have played a key role in identifying best candidates
  - PM machines combined with CSI power electronics has emerged as the most promising approach for designing IMDs to achieve performance metrics
- 2nd year will focus on converting IMD concept into a preliminary design for evaluation
  - Multi-physics analysis will be critical for optimizing design for highest performance
  - Retire key technical risks using experimental benchtop prototype inverter

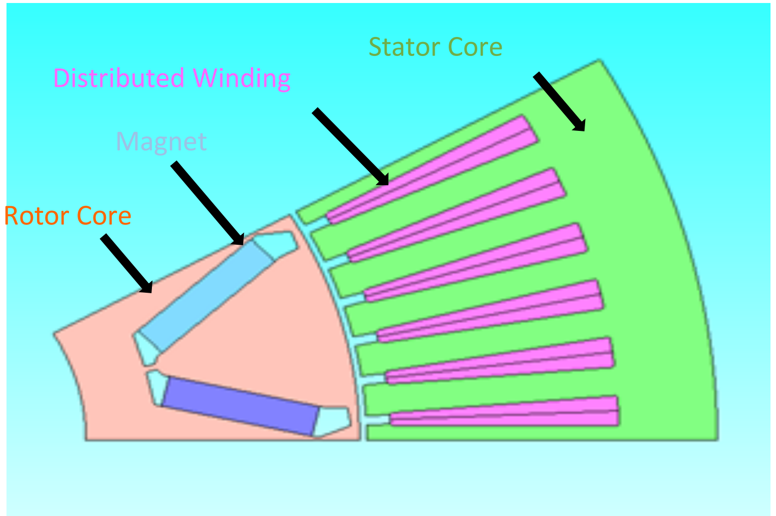
Promising start for developing advanced IMD to meet DOE objectives

Technical Backup Slides

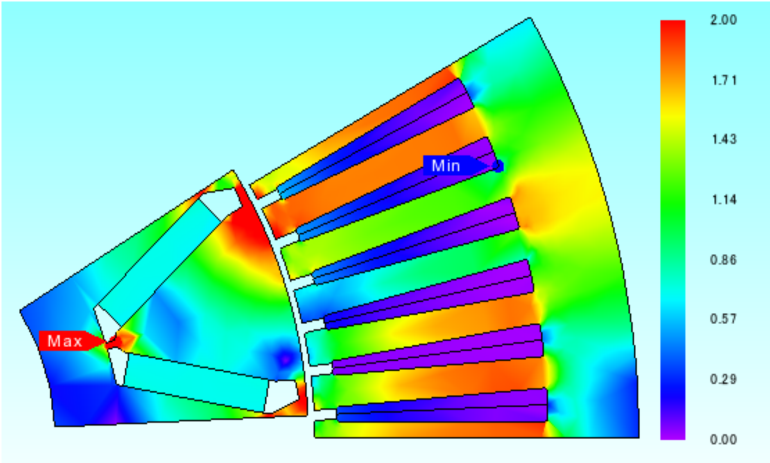
Technical Accomplishments and Progress

Interior PM Machine with Distributed Winding Traction Motor Design Details

IPM machine with distributed winding

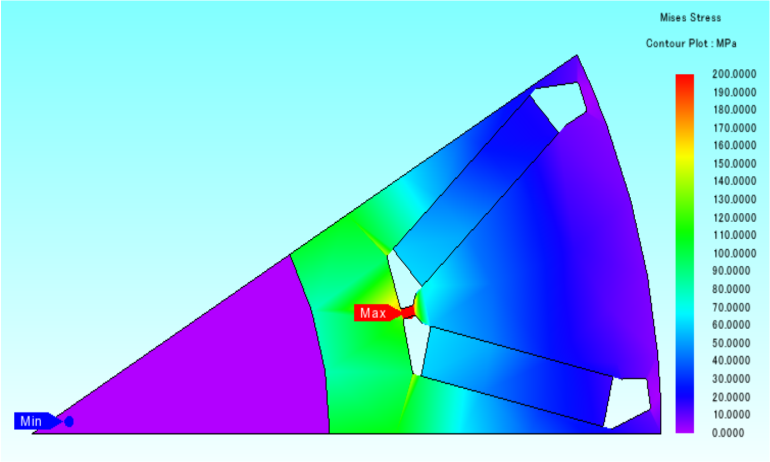


Flux density distribution IPM machine at peak condition

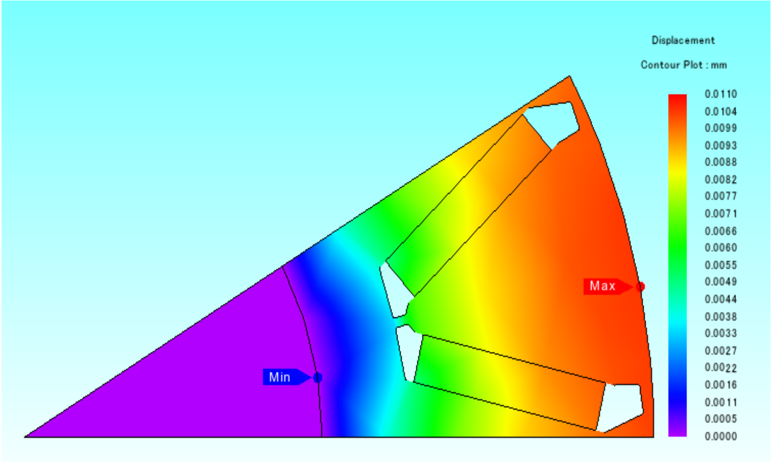


Parameter	Value
Stator/rotor material	10JNHF600
Magnet material	N38 NdFeB *No dysprosium*
Stator slots / Rotor poles	72/12
Rotor corner speed [rpm]	3,200
Rotor max speed [rpm]	20,000
Rated Power [kW]	55
Peak Power [kW]	100
Peak Power density [kW/l]	22.9
Efficiency @ 55 kW	96.5

Von-Mises stress



Displacement

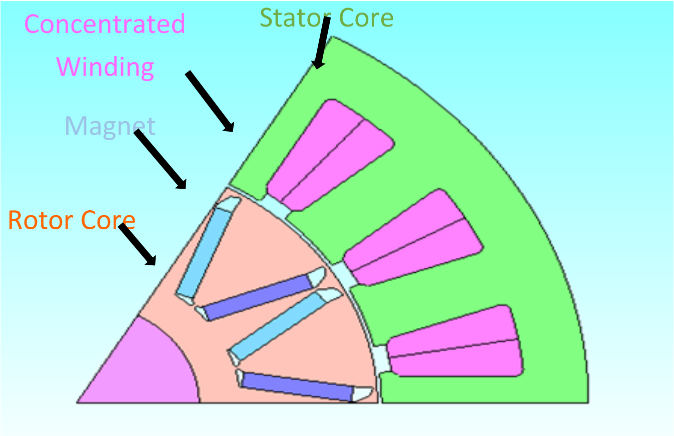


IPM machine with distributed winding has been investigated to meet the requirements

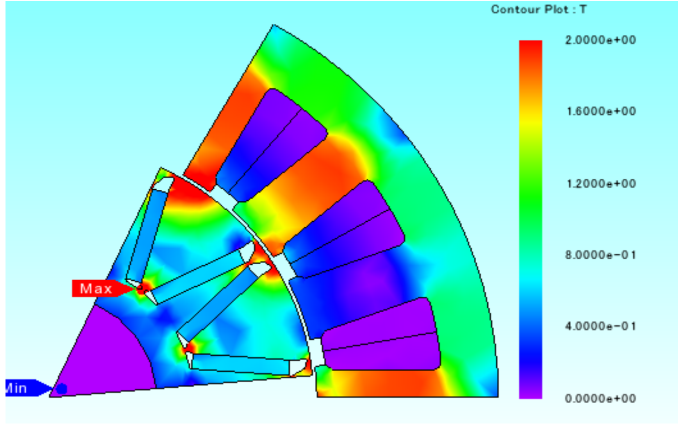
Technical Accomplishments and Progress

Interior PM Machine with Concentrated Winding Traction Motor Design Details

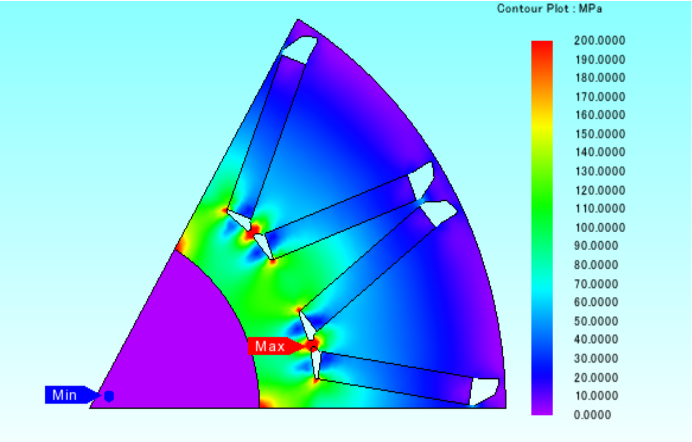
IPM machine with concentrated winding



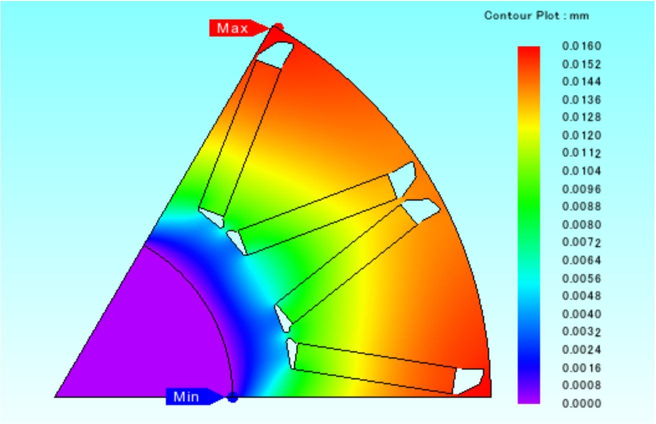
Flux density distribution IPM machine at peak condition



Von-Mises stress



Displacement



Parameter	Value
Stator/rotor material	10JNHF600
Magnet material	N38 NdFeB *No dysprosium*
Stator slots / Rotor poles	18/12
Rotor corner speed [rpm]	3,200
Rotor max speed [rpm]	20,000
Rated Power [kW]	55
Peak Power [kW]	100
Peak Power density [kW/l]	21.5
Efficiency @ 55 kW	95.5

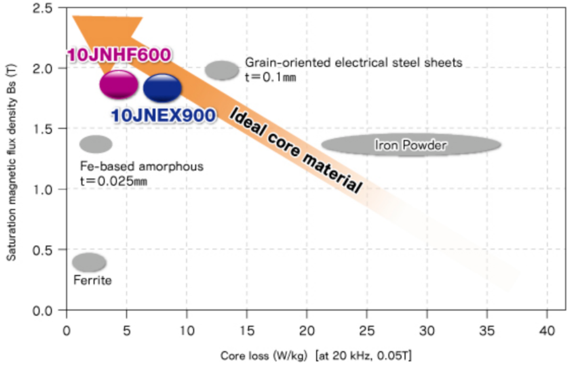
IPM machine with concentrated winding has been investigated to meet the requirements

Technical Accomplishments and Progress

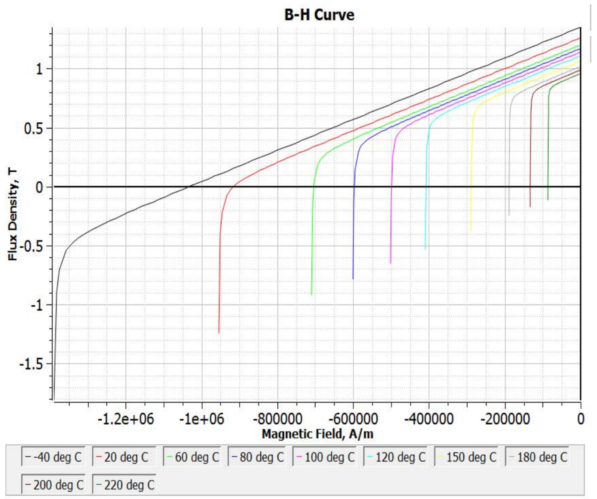
Investigation of New Motor Designs and Materials

– Investigated new motor technologies including following

- High-energy magnet materials with high temperature capability (no heavy rare earth)
- Insulation materials with high thermal conductivity, low weight and volume, and corona resistance
- Lightweight and high-strength composite materials
- Advanced electromagnetic design incorporating various materials and structural advances
- Advanced thermal management concepts



JFE super core

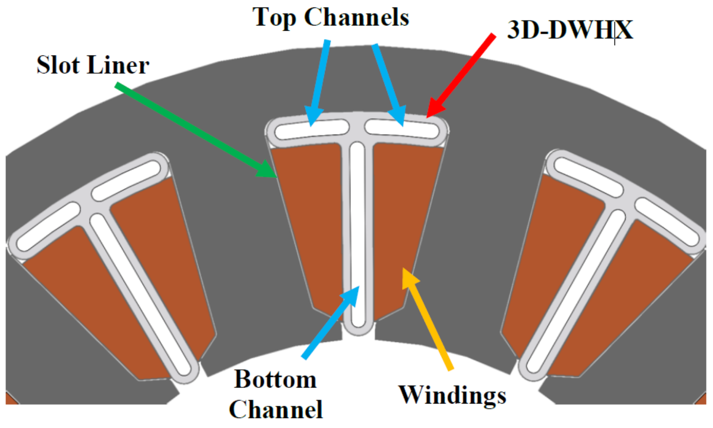


B-H curve of N38 NdFeB magnet

TABLE II PROPERTIES FOR INSULATION MATERIAL

Property	Value
Thermal conductivity [W/mK]	1.9
Dielectric strength [kV/mm]	18.5
Mixed specific gravity @25°C	2.73

CoolTherm EP-2000 from Lord



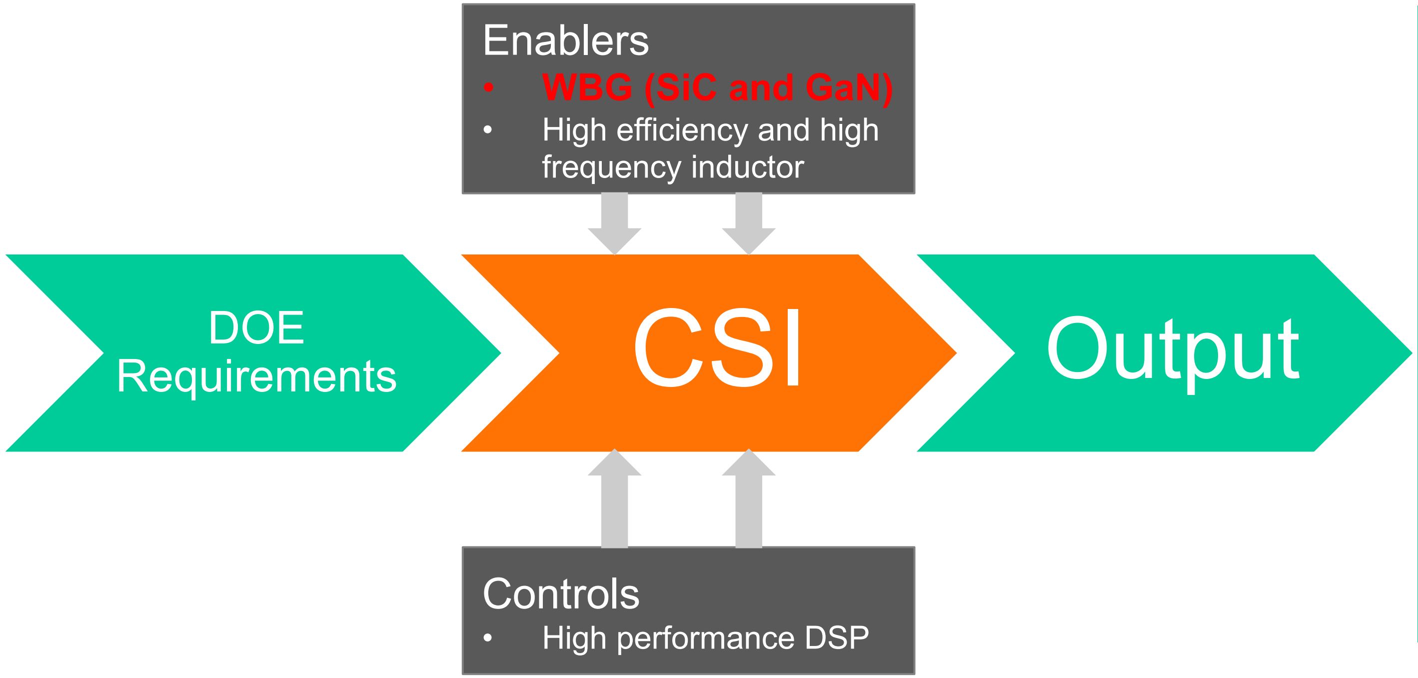
3D-DWHX concept in a stator

TORAYTORAYCA Carbon fiber

Identified the best materials for our project from our survey for high energy magnet, insulation materials, composite materials, electromagnetic design, and thermal management

Technical Accomplishments and Progress

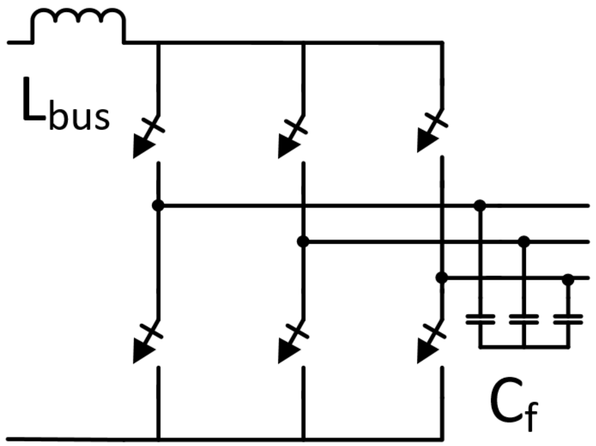
Current Source Inverter with WBG devices



High power density
High efficiency
Good EMI/EMC performance
- Output voltage almost sinusoidal

Low PWM harmonics
Good field weakening capability
- Output voltage boost function

High temperature capability
- No DC Link capacitor



CSI configuration

- Current source inverter (CSI) is a ***dual topology*** of traditional VSI
- The dc-link capacitor in the VSI is replaced by the ***dc-link inductor***, and three small capacitors are added at CSI's output terminals
- The dc-link inductor of CSI can be dramatically reduced in mass and volume because of ***high switching frequency*** values of WBG
- The ***high-frequency WBG*** switches is the enabler for CSI to come back
- The CSI has less EMI issue than VSI because of filtering effect of output capacitors for the output voltage.

Technical Accomplishments and Progress

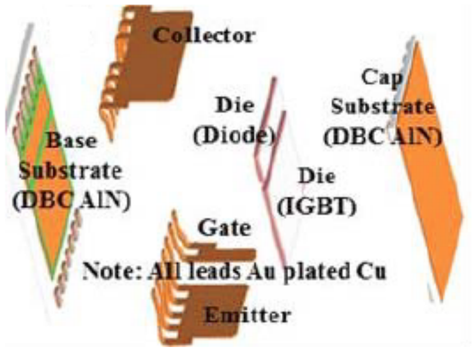
Survey on WBG devices, passive components, and cooling methods

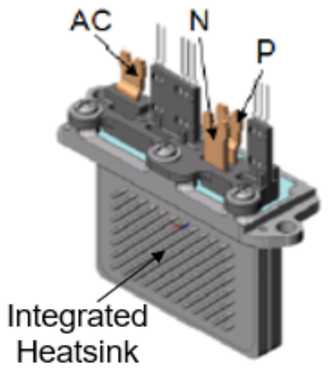
- Surveyed and analyzed WGB (SiC and GaN) power semiconductor devices
  – Investigated FET + Diode vs FET + FET configuration for RVB switch for CSI

Company	Part No.	Vds (V)	Id @ 25C (A)	Rds @ 25℃ (Ω)	Packaging
Transphorm	TP65H050BS*	650	34	0.05	TO-263
Transphorm	TP90H050WS*	900	34	0.050	TO-247
GaN Systems	GS-065-150-1-D	650	150	0.01	Die
OnSemi	NVHL080N120SC1OS-ND	1200	44	0.11	TO-247
Littelfuse Inc	LSIC1MO120E0120	1200	27	0.150	TO-247
CREE	C3M0016120K	1200	115	0.016	TO-247
CREE	C2M1000170D	1700	4.9	1.1	TO-247
CREE	CAB450M12XM3	1200	450	NA	Half-Bridge
GeneSiC	GA50JT12-247	1200	100	0.025	TO-247
GeneSiC	GA08JT17-247	1700	8	0.25	TO-247
ROHM	SCT3017ALHRC11	650	118	0.0221	TO-247
ROHM	SCT3022KLHRC11	1200	95	0.0286	TO-247

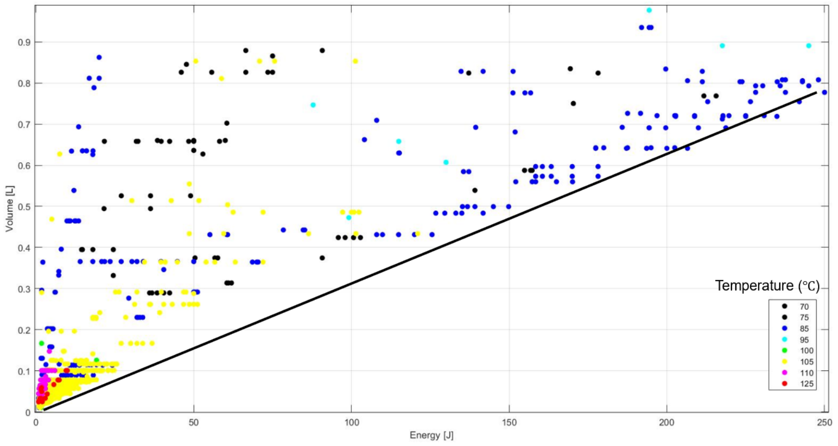
- Investigated various cooling methods used in EVs including power device cooling

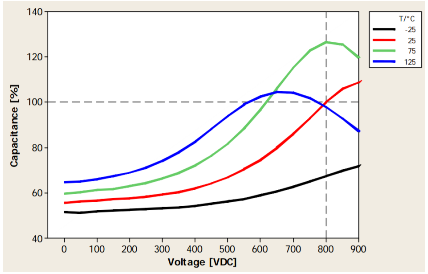
Chevrolet VOLT-2





- Survey and analyze for state-of-the-art passive components
  – Characterize capacitor volume vs. capacitance
  – Compared ceramic vs. film capacitors
  – Looked at various inductor materials and carried out preliminary inductor designs





We successfully reviewed and analyzed recent technical developments that will enable high power density traction drive system